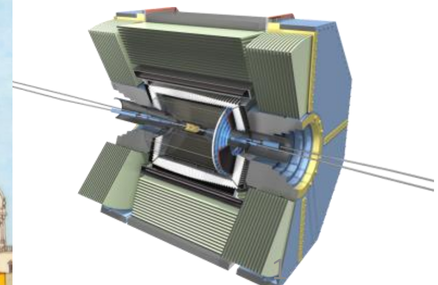
Quarkonium at Belle II

Vishal Bhardwaj
IISER Mohali
(for the Belle II collaboration)

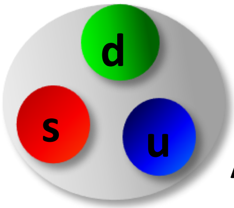
5-10 September 2021



Outline of the talk

- Motivation for spectroscopy
- Spectroscopy at *B* factories
- Belle to Belle II
- Prospects of charmonium spectroscopy in Belle II
- Bottomonium spectroscopy prospects
- Summary

QCD : real particles are color singlet

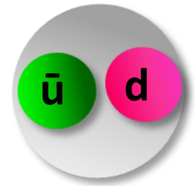


Baryons are red-blue-green triplets

Λ=usd

Mesons are color-anticolor pairs

π=ūd

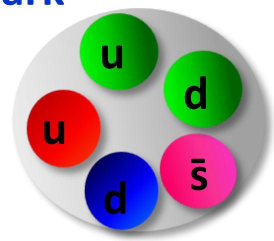


Other possible combinations of quarks and gluons : **exotic**

artistic illustration

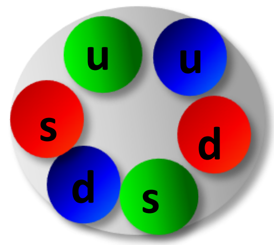
Pentaquark

S= +1 Baryon



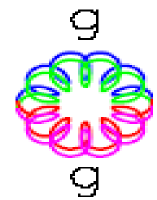
H di-Baryon

Tightly bound 6 quark state



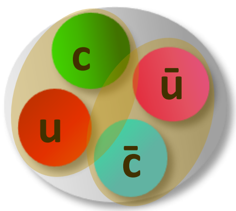
Glueball

Color-singlet multi-gluon bound state



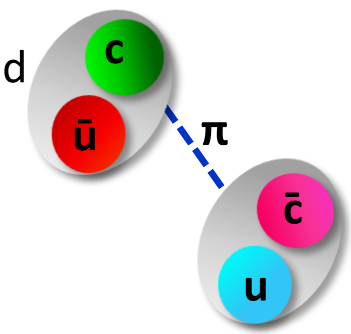
Tetraquark

Tightly bound diquark & anti-diquark

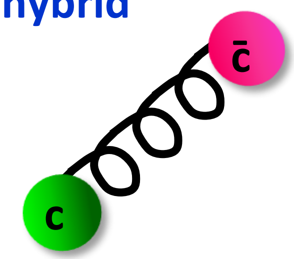


Molecule

loosely bound meson-antimeson "molecule"



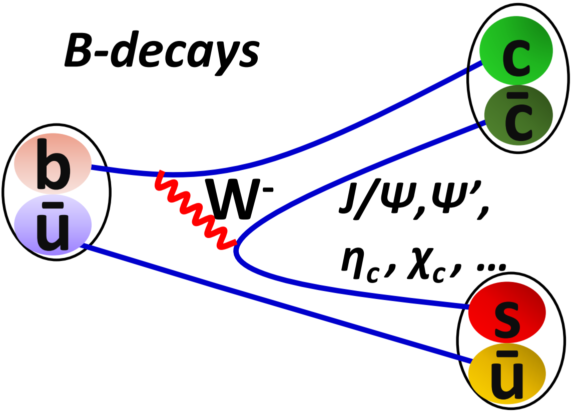
qq̄ -gluon hybrid mesons



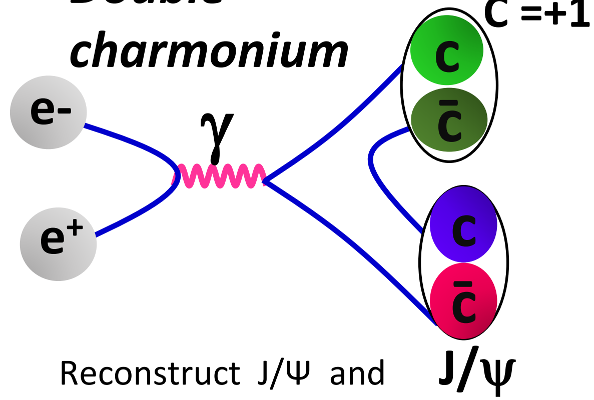
- **$q\bar{q}$ spectroscopy with heavy quark (mostly *c* or *b*) are best place to study quark model.**
- **Simple two body system, non-relativistic and narrow (with OZI suppression).**
- **Further, one can search for exotics with them.**

Production of $q\bar{q}$ (-like) *@ B-factories*

B-decays

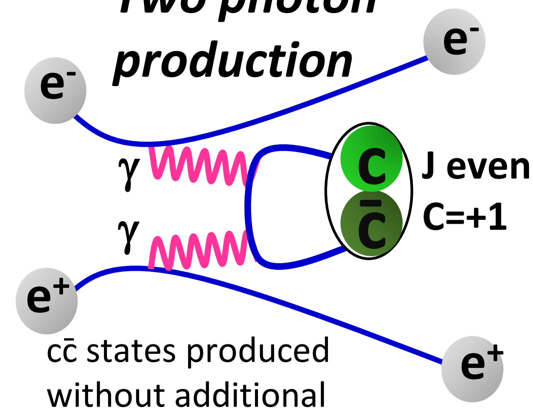


Double charmonium



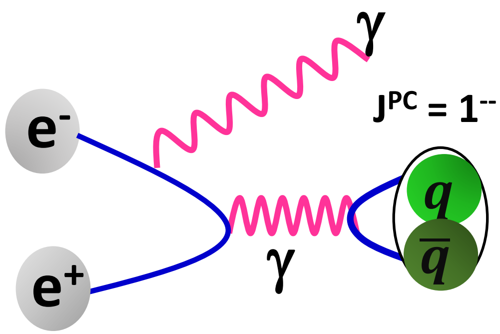
Reconstruct J/Ψ and look at recoil mass

Two photon production



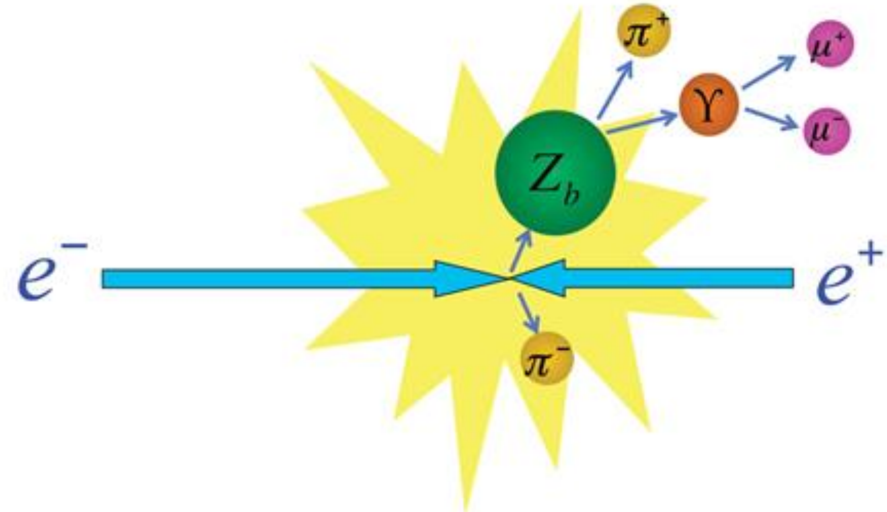
$c\bar{c}$ states produced without additional hadrons.

Initial state radiation

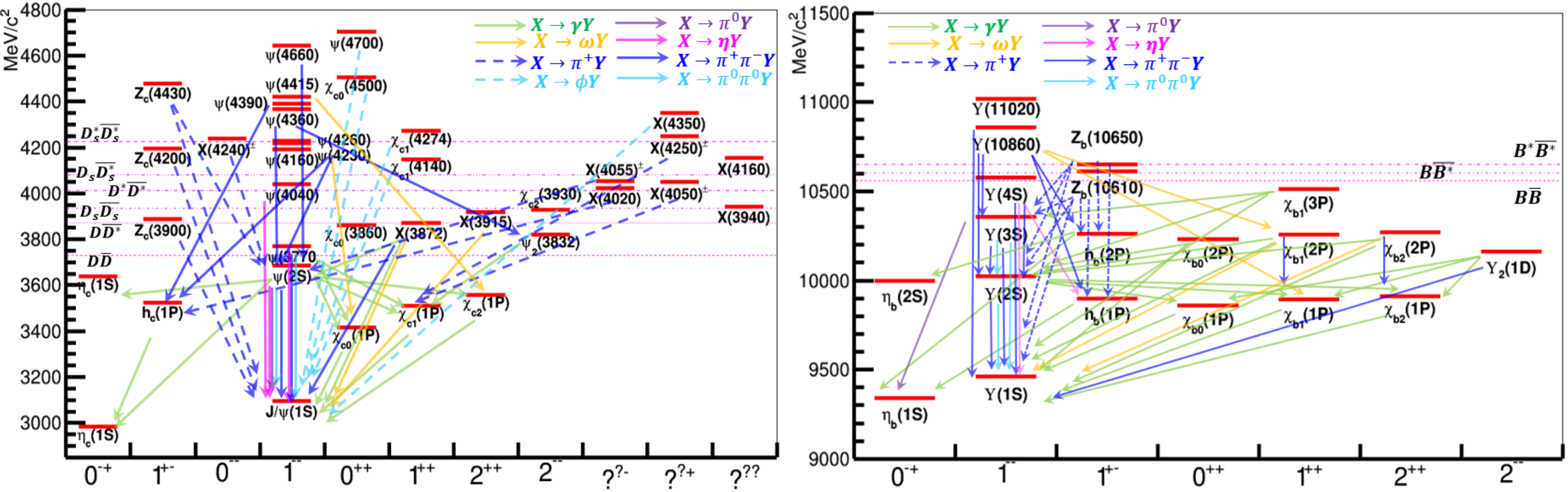


Annihilation at smaller energy.

Quarkonium decay/transitions



$q\bar{q}$ (-like) states till now

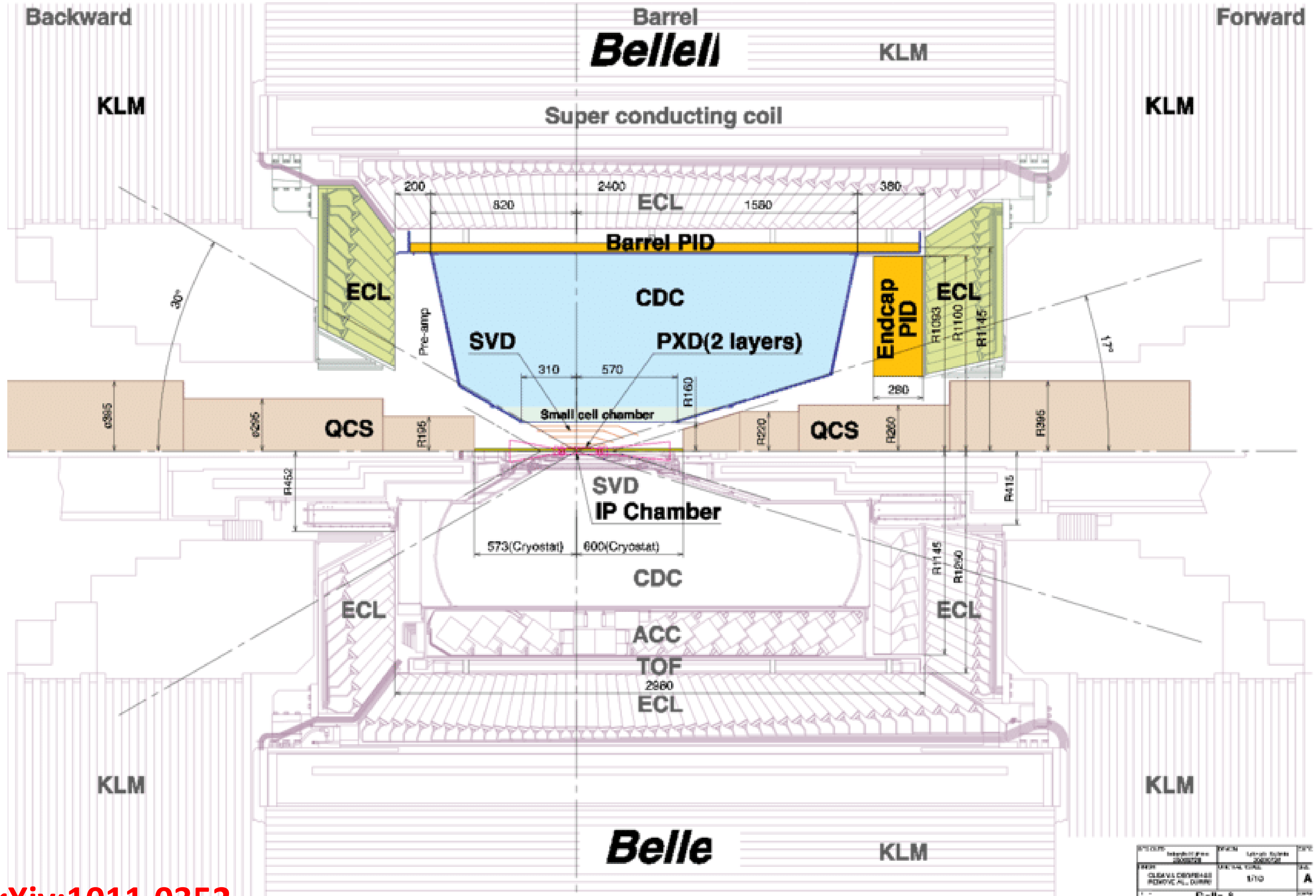


- 17 years have passed after the discovery of first $c\bar{c}$-like [*X(3872)*] by the Belle collaboration.
- Plenty of states have been found.
- Several states found in one process (not easy to understand).
- States have non-zero charge, suggesting them to be tetraquark/molecule-like state.
- Instead of conventional spectroscopy, it is now *exotic spectroscopy*.
- However, the limited statistics always come as the evil limiting factor.

Belle II (with ability to accumulate 50 times* more data in comparison to Belle) can play crucial role in understanding these states.

*Thanks to super KEKB

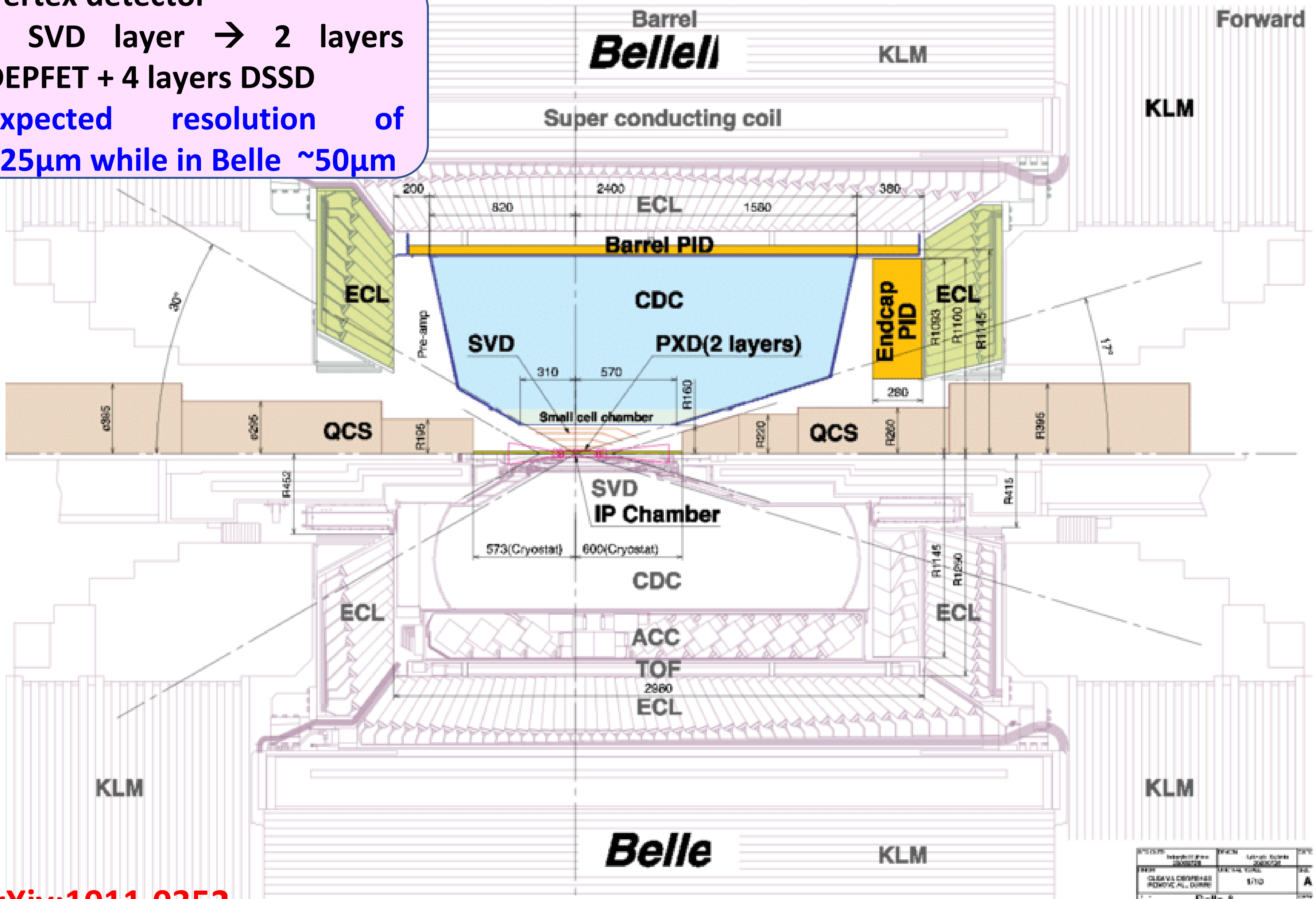
Belle to Belle II



arXiv:1011.0352

Belle to Belle II

Vertex detector
4 SVD layer → 2 layers DEPFET + 4 layers DSSD
Expected resolution of ~25μm while in Belle ~50μm



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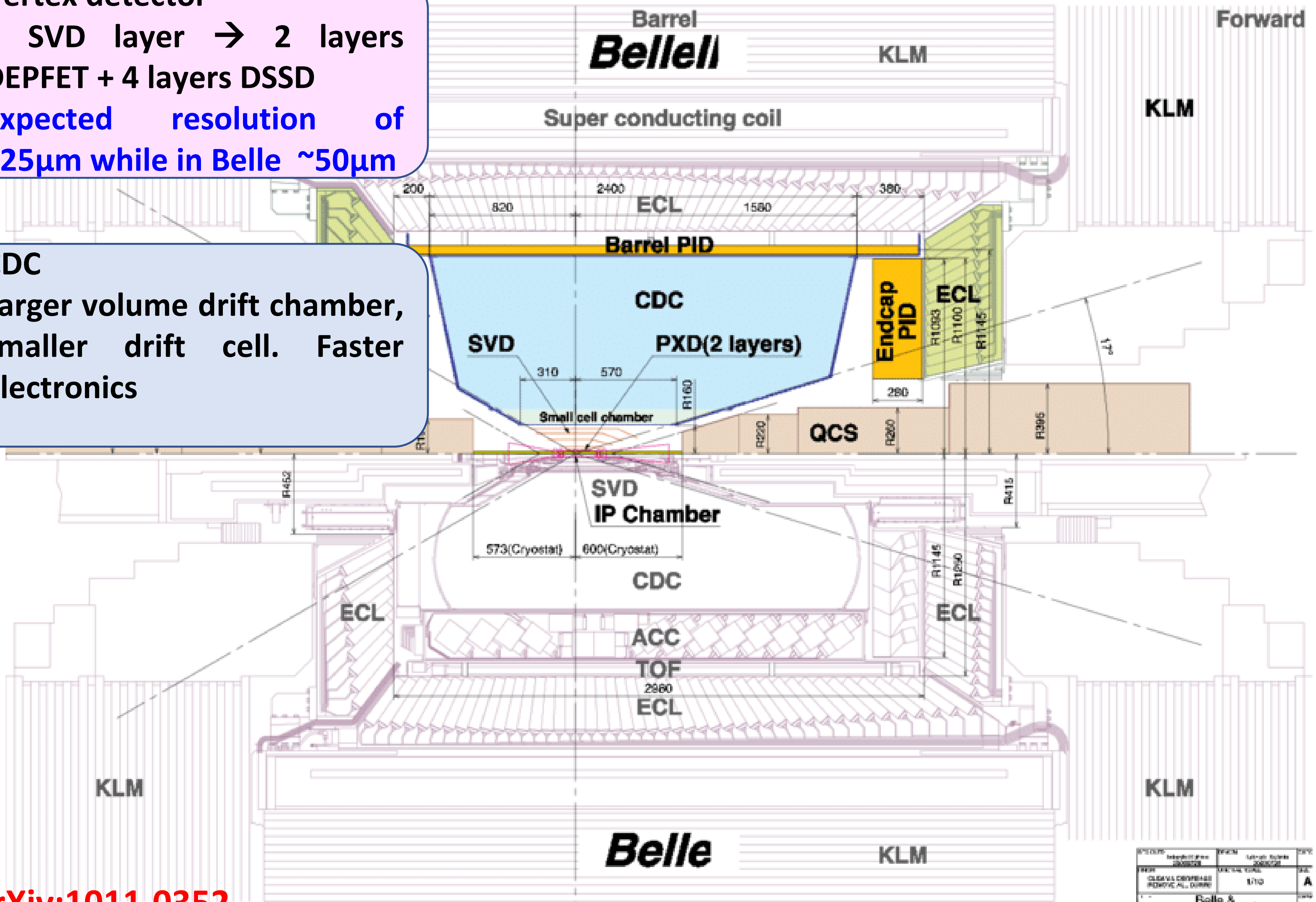

CDC
Larger volume drift chamber, smaller drift cell. Faster electronics

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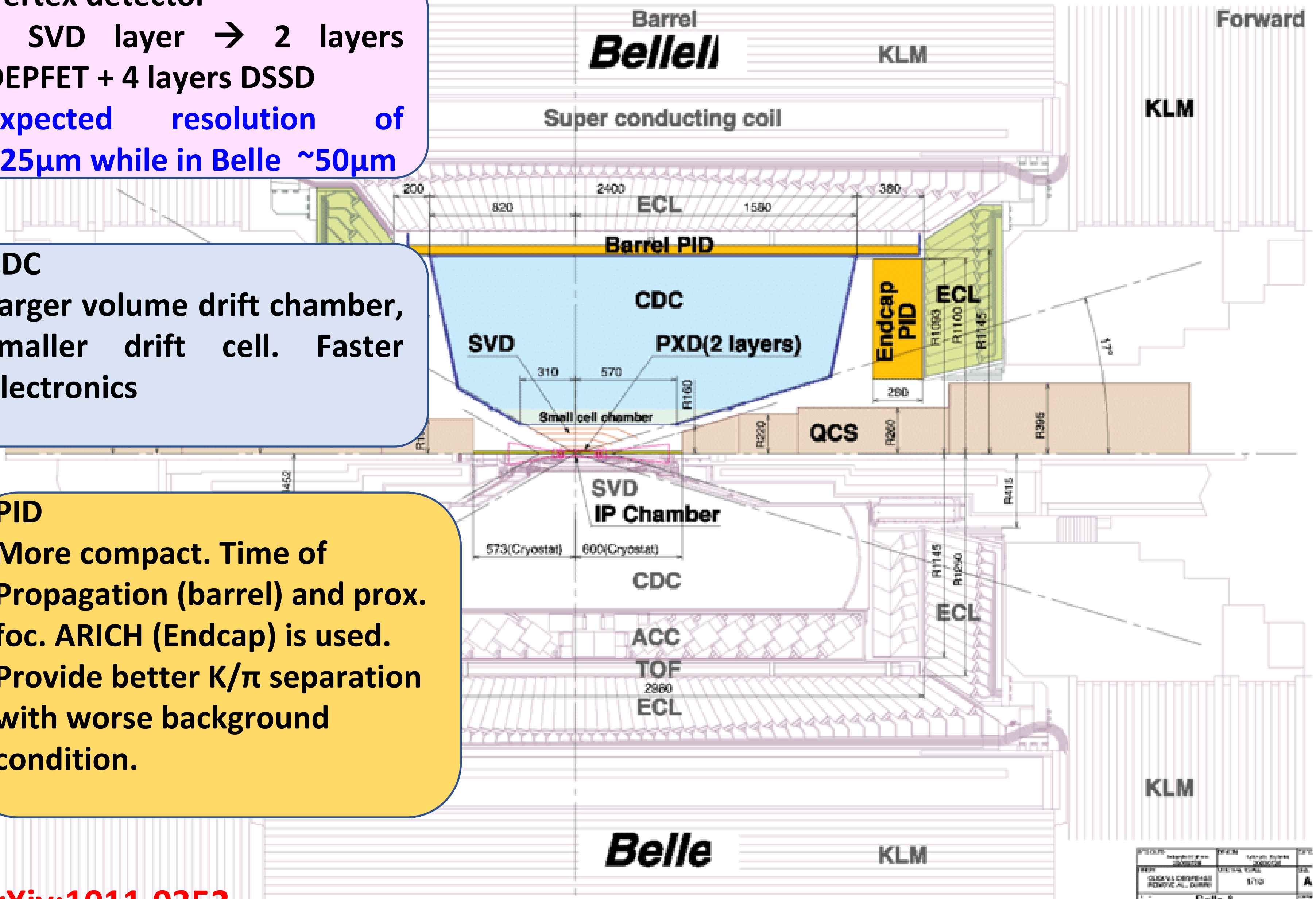
PID
More compact. Time of Propagation (barrel) and prox. foc. ARICH (Endcap) is used. Provide better K/π separation with worse background condition.



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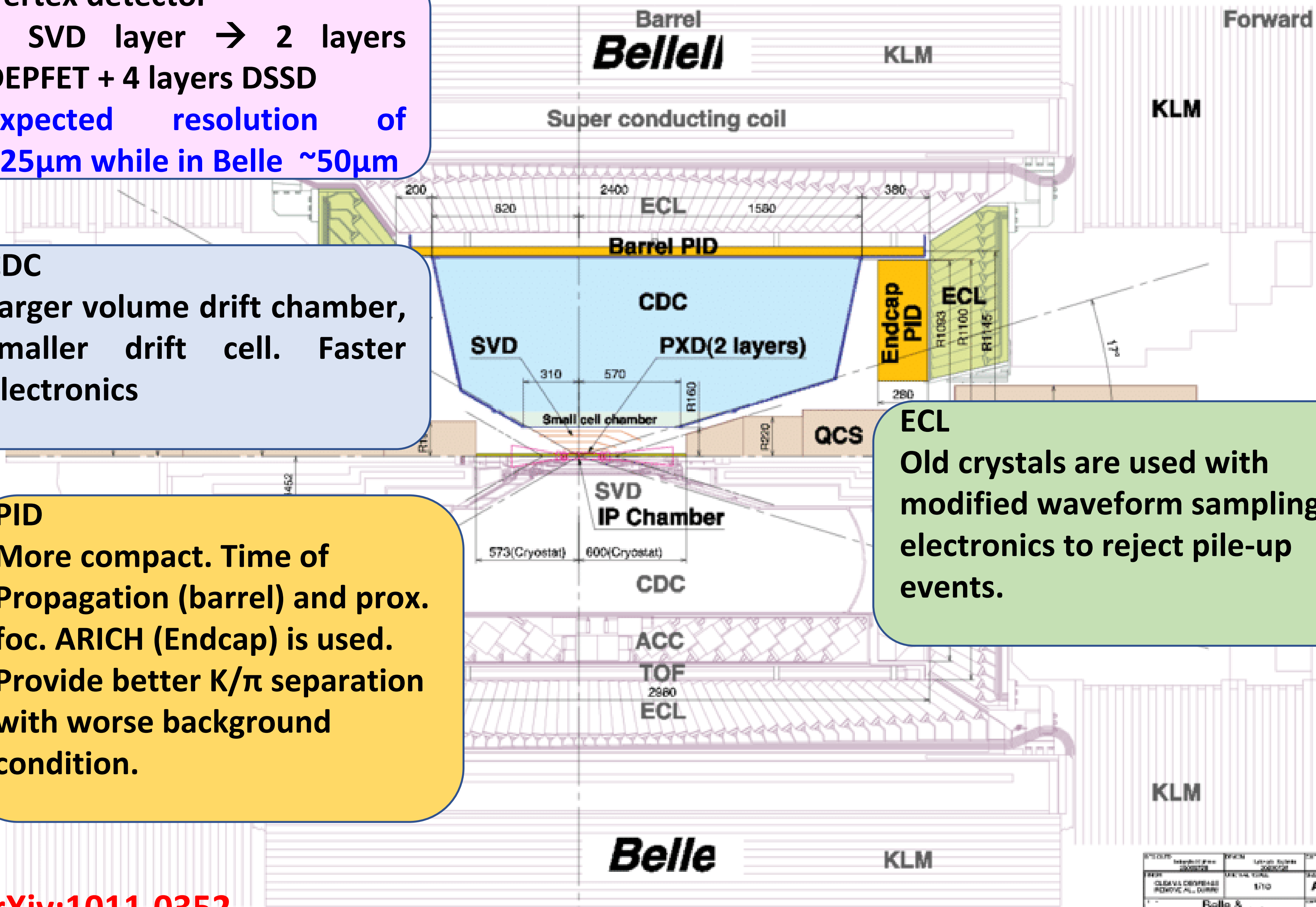

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ECL
Old crystals are used with modified waveform sampling electronics to reject pile-up events.

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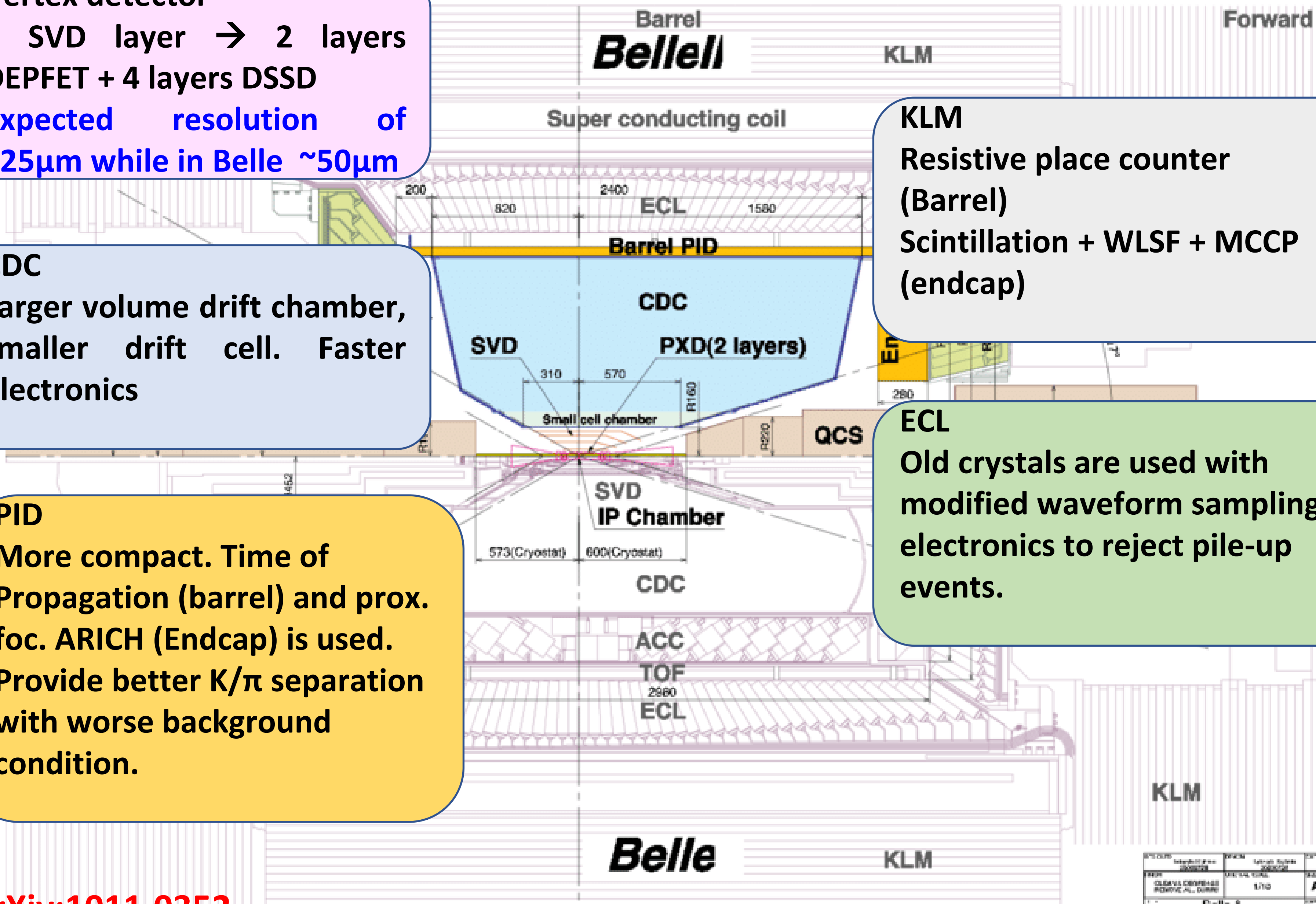
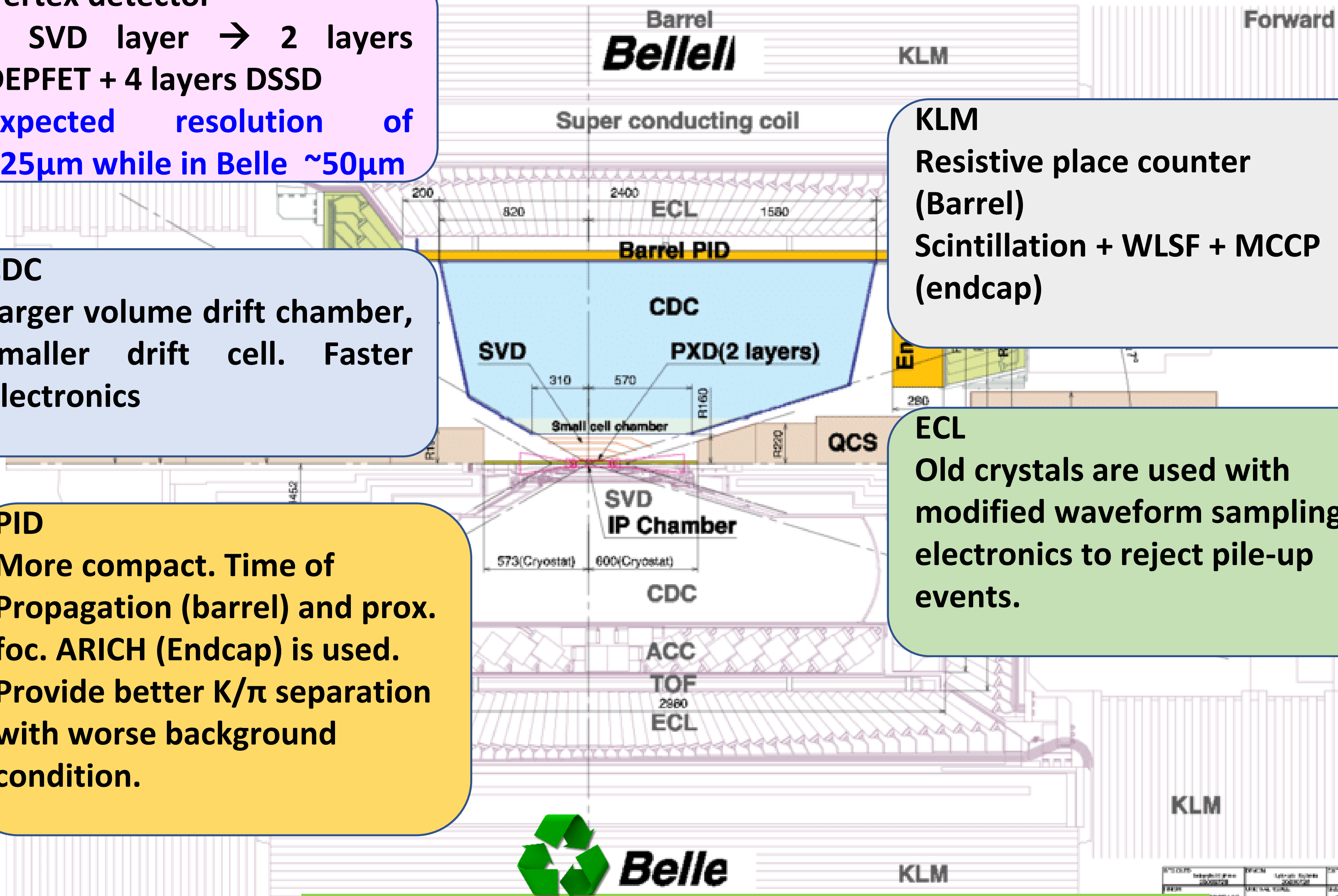


KLM
Resistive place counter (Barrel)
Scintillation + WLSF + MCCP (endcap)

ECL
Old crystals are used with modified waveform sampling electronics to reject pile-up events.

arXiv:1011.0352

Belle to Belle II



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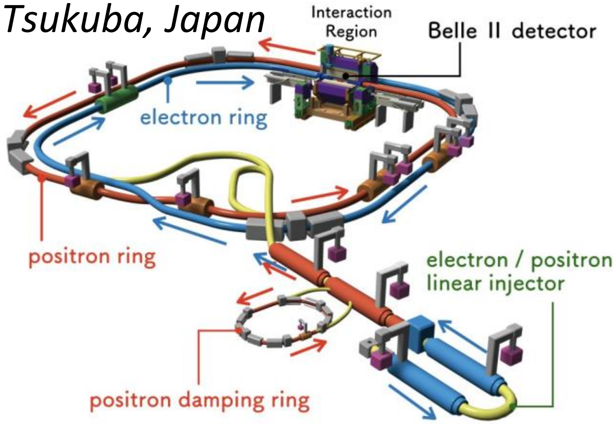
arXiv:1011.0352

ECL crystals and part of KLM sub-detector are re-used.

SuperKEKB: asymmetric *e-*(7GeV) - *e+*(4 GeV) Collider

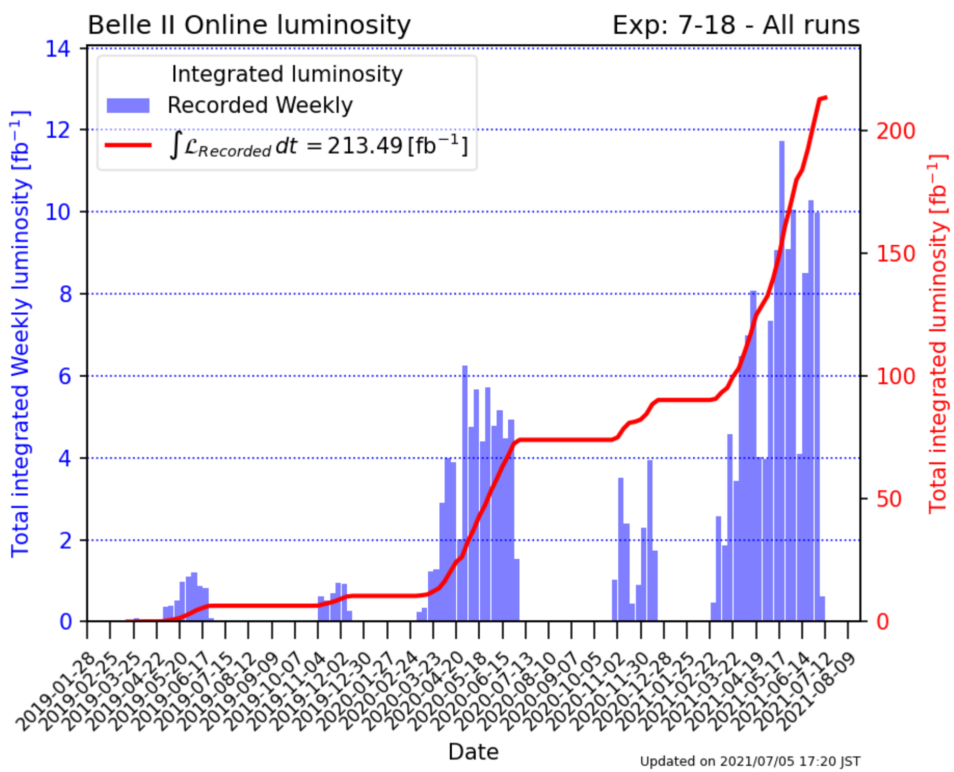
Tsukuba, Japan

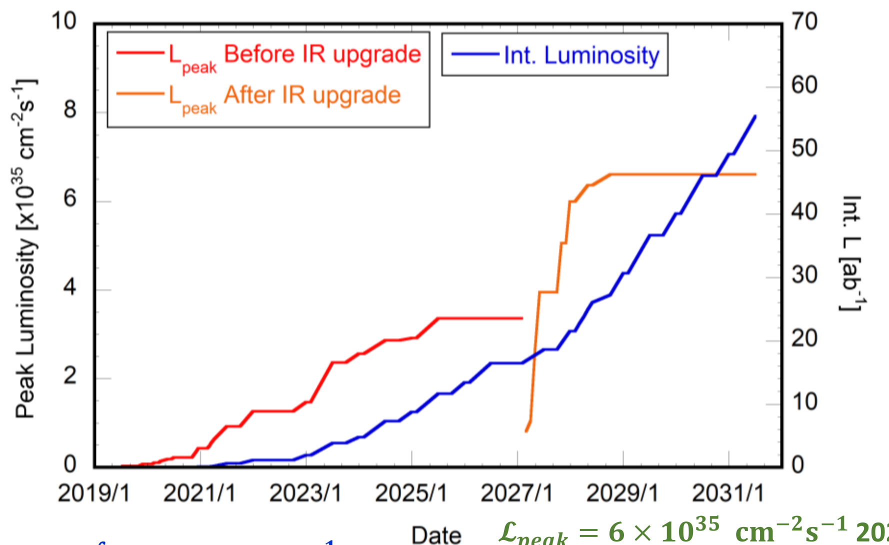


Goal > ~ 30 x KEKB instantaneous luminosity $\mathcal{L}$ =$6 \times 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Luminosity record : $3.1 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

SuperKEKB breaks the *world record* for integrated luminosity in a single month and integrates 40.3 fb^{-1} in May 2021.





$\mathcal{L}_{peak} = 6 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ **2029**

$\int \mathcal{L} = 0.5 - 1\ \mathrm{ab}^{-1}$ **2022**

$\int \mathcal{L} = 10\ \mathrm{ab}^{-1}$ **2026**

$\int \mathcal{L} = 50\ \mathrm{ab}^{-1}$ **2031**

Starting from the start: X(3872)

Most probable explanation:

Molecule with admixture of charmonium *(seems to be choice for now, others not ruled out yet).*

Precise Mass and Width studies.

✓ Expected yield of $B^+ \to X(3872)(\to J/\psi\pi\pi)K^+$ ~ 1500 events (with 10 ab^{-1})$

✓ Current yield of $B^+ \to \psi'(\to J/\psi\pi\pi)K^+$ is ~3600 events (at Belle).

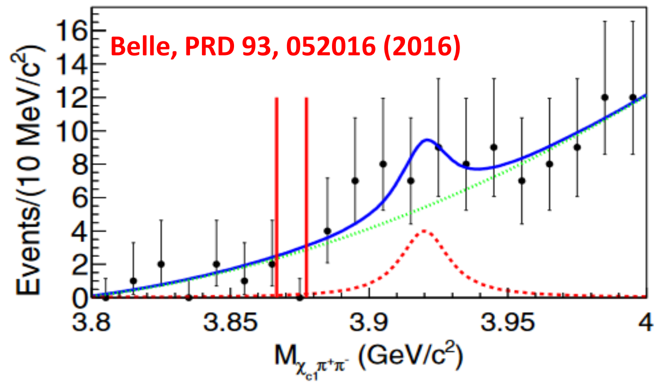
BESIII,PRL 122, 202001 (2019)

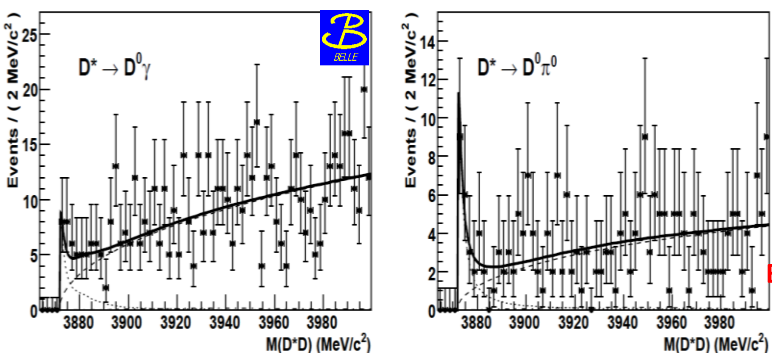
- BESIII measured $\frac{\mathcal{B}(X(3872)\to\chi_{c1}\pi^0)}{\mathcal{B}(X(3872)\to J/\psi\pi^+\pi^-)} = 0.88^{+0.33}_{-0.27} \pm 0.10$

Belle, PRD 99, 111101 (R) (2019)

- Belle measured same ratio as < 0.97 (@90%).
- If X(3872) structure is dominated by χ'_{c1} component, we expect $X(3872) \to \chi_{c1}\pi^+\pi^-$ to be there.
- Belle II should be able to observe

  $X(3872)$ or $\chi_{c1}' \to \chi_{c1}\pi^+\pi^-$





Belle,PRD 81, 031103 (2010)

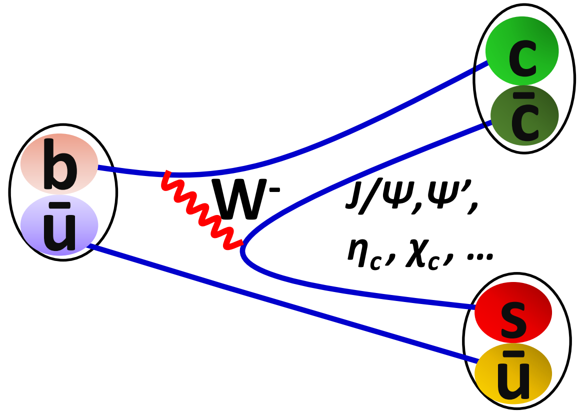
Informative to study $X(3872) \to \overline{D^0}D^{*0}$ in Belle II data

Mass $\to$ $3872.9^{+0.6}_{-0.4}\,^{+0.4}_{-0.5}$ MeV/c²

- At Belle II, possible to study $J/\psi\,\pi^+\pi^-$ and DD^*, the coupling will provide information about the X(3872) nature.

$1/5 of total data

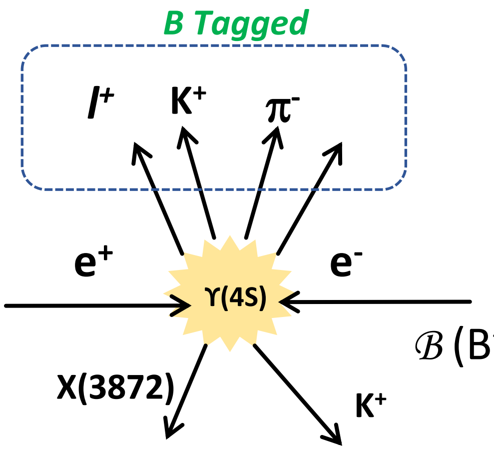
Production of X(3872)



"Measuring absolute" $\mathcal{B}$(B→X(3872)K⁺) will help in measuring $\mathcal{B}$(X(3872)→ final state).

Measurement is "only possible at B factories"

(operating at center-of-mass energy of ϒ(4S) which decays into $B\bar{B}$ pairs)

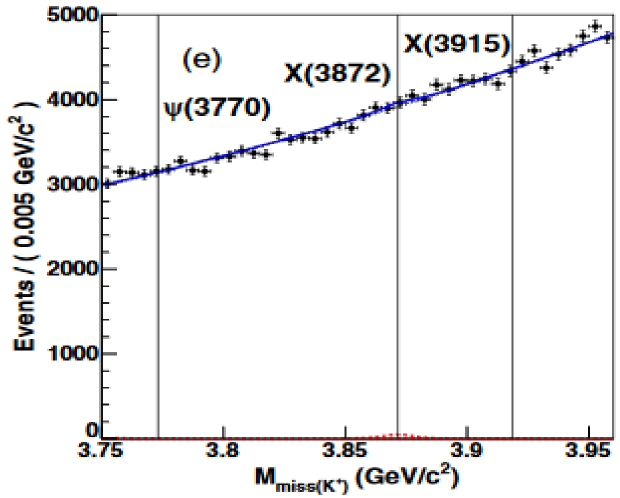


Missing mass recoiling against K^+

$$M_{miss} = \sqrt{(p^*_{e^+e^-} - p^*_{tag} - p^*_h)^2}$$

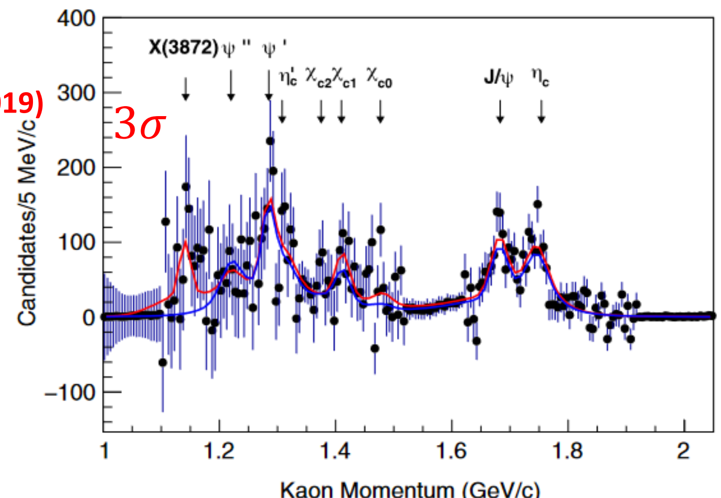
$\mathcal{B}$(B⁺→X(3872)K⁺) < 2.6 x 10^{-4} (@ 90% CL)

Belle, PRD 97, 012005 (2018)



$\mathcal{B}$(B⁺→X(3872)K⁺) = (2.6 ± 0.6 ± 0.5) x 10^{-4}

BaBar, PRL 124, 152001 (2019)



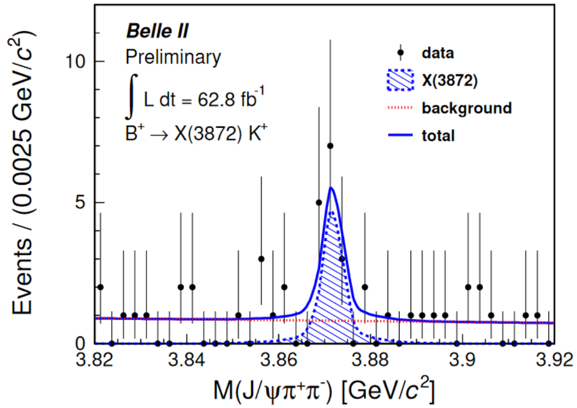
Belle II might measure this value.

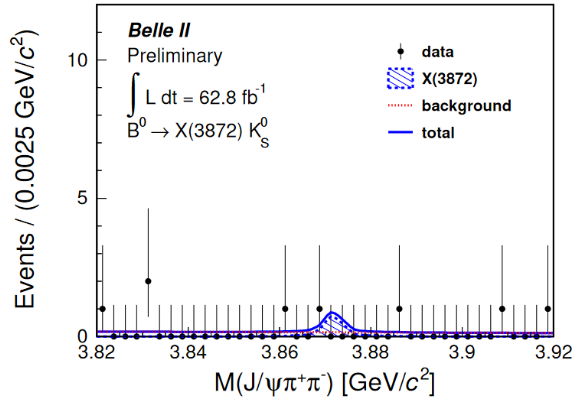
- ➢ Not only for X(3872), but also for other states.
  - ❖ Able to measure by 7σ (*naïve estimation*).

Improved "hadronic tagging" software at Belle II !

Rediscovery of X(3872)

BELLE2-NOTE-PL-2021-002





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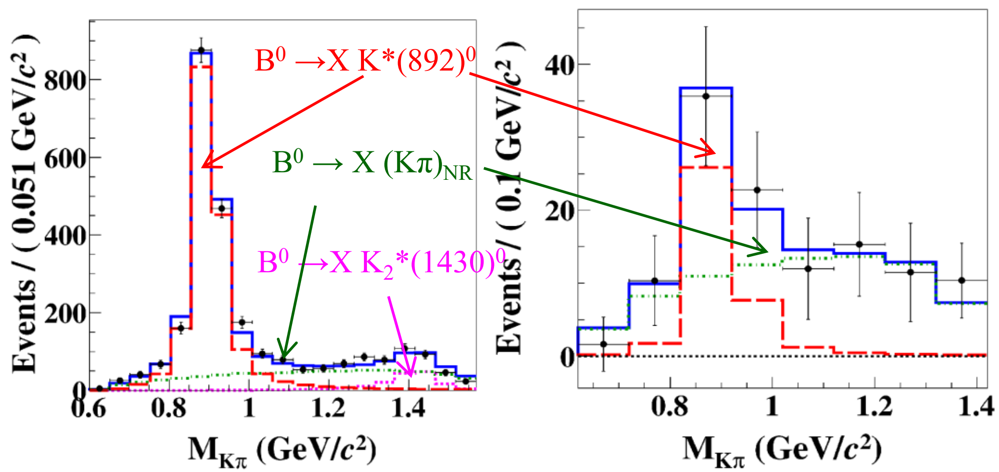
Rediscovery of X(3872) with 14.4 ± 4.6 signal events (4.6σ) at Belle II.

$B \to X(3872)K\pi$ decay

Belle, PRD91, 051101 (R) (2015)

K*(892)^0 component in (Kπ) system in X(3872) does not dominate, *"in marked contrast"* to ψ' case.

With 10 ab^{-1}, Belle II will measure this precisely.



B→ ψ'K$^+$π$^-$

B→X(3872)K$^+$π$^-$

Events will be similar to what we have now for ψ'.

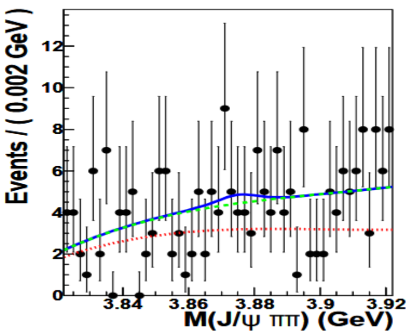
Decays of *X(3872)*

Measuring ratios of radiative decays

$\mathcal{B}(X(3872)\to\psi'\gamma)/\mathcal{B}(X(3872)\to J/\psi\gamma)$	= 3.5 ±1.4	BaBar,PRL 102, 132001 (2009)
	< 2.1 (@90% CL)	Belle,PRL 107, 091803 (2011)
	= 2.46±0.64±0.29	LHCb, NPB 886, 665 (2014)
	<0.59 (@90% CL)	BESIII,PRL 124, 242001 (2020)

Expected yield of $B^+\to X(3872)(\to J/\psi\gamma)K^+$: ~ 400 events (with 10 ab^{-1})
Need to resolve the conflict. Belle II should be able to do this and measure the above mention ratio precisely in order to constraint the admixture.

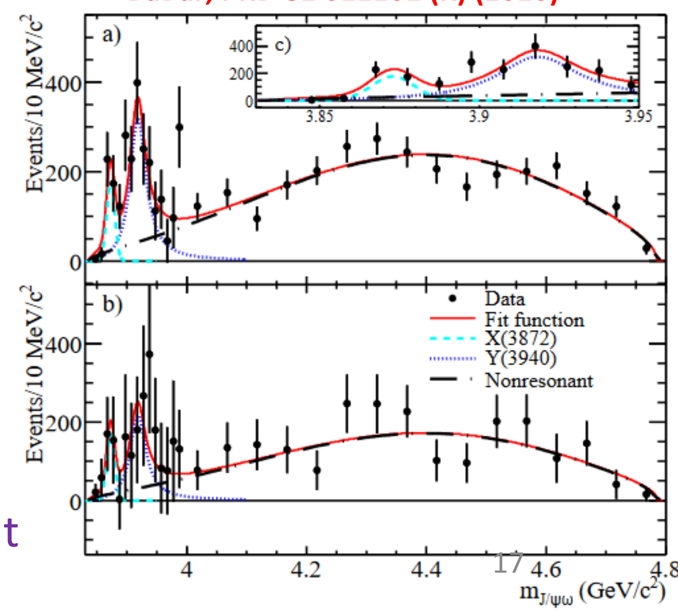
Charged partner of X(3872) Belle, PRD 84, 052004 (2011)



Negative search
$\mathcal{B}(B^0\to X(3872)^+K^-)/\mathcal{B}(X(3872)^+\to J/\psi\pi^+\pi^0) < 4.2 \times 10^{-6}$
If found, will be very promising for the tetraquark picture.

Absence of charged partner suggest X(3872) to be an iso-singlet state.

BaBar, PRD 82 011101 (R) (2010)



Suggests $X(3872)\to J/\psi\pi^+\pi^-$ is iso-spin violating decay ?
Belle, BaBar, BES III measured the allowed $X(3872)\to J/\psi\pi^+\pi^-\pi^0$

$$\frac{\mathcal{B}(X(3872)\to J/\psi\omega(\to\pi^+\pi^-\pi^0))}{\mathcal{B}(X(3872)\to J/\psi\pi^+\pi^-)} = 0.8\pm0.3 \quad , \quad 1.43^{+0.28}_{-0.23}$$

BaBar, **PRD82** 011101 (2020) ; BESIII, **PRL122** 232002 (2019)

Belle II should measure this ratio.

- One can also measure $\mathcal{B}(B^+\to X(3915)\,K^+)$.
- Searching for the molecular/tetraquark partners are important tasks that can be done at the Belle II.

Other production

Two photon processes

Study of $\chi_{c2}(3930)$ using $\gamma\gamma \rightarrow Z(3930) \rightarrow D\bar{D}$

Mass and width precision study.

$X(3915)$ (thought to be $\chi_{c0}(2P)$)was discovered in two photon process.

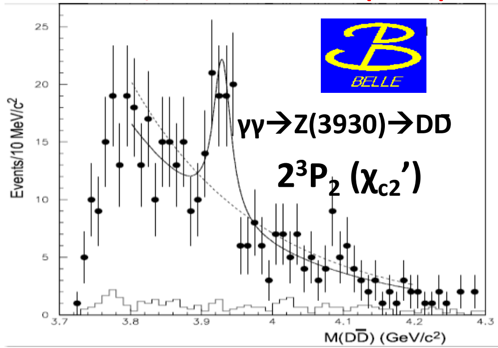
Currently, $\chi_{c0}(2P)$ has been suggested to be recently found $X(3860)$ in $J/\psi D\bar{D}$.

Belle observed $X(4350)$ in $\gamma\gamma \rightarrow J/\psi\phi$.

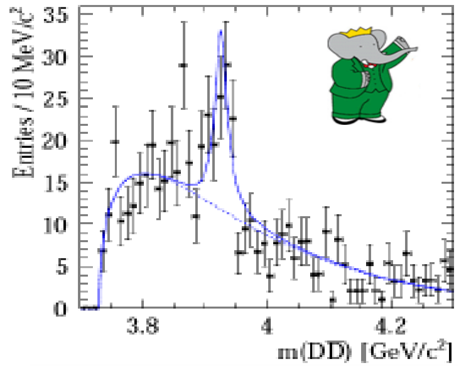
Recently, LHCb did amplitude analysis of $B \rightarrow J/\psi\phi K$, found several structures $Y(4140)$, $Y(4274)$, $X(4500)$, $X(4700)$ but not $X(4350)$ (?)

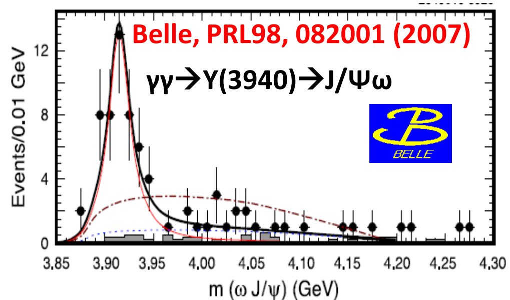
Belle II should revisit with more data.

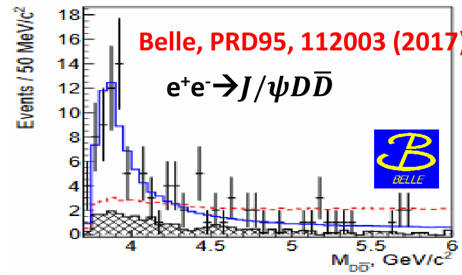
Belle, PRL 96 082003 (2006)



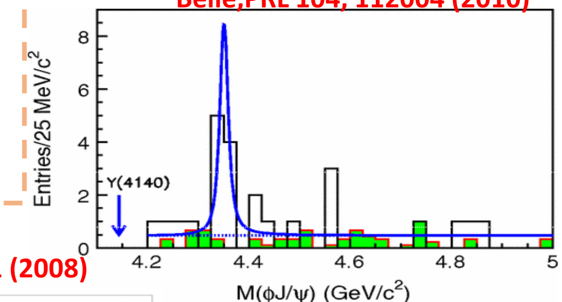
BaBar, PRD81 092003 (2010)



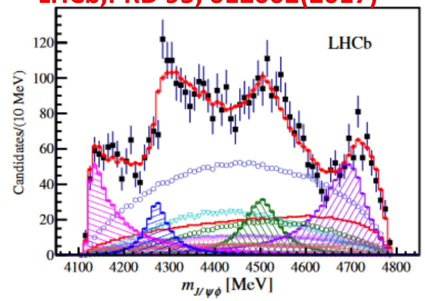




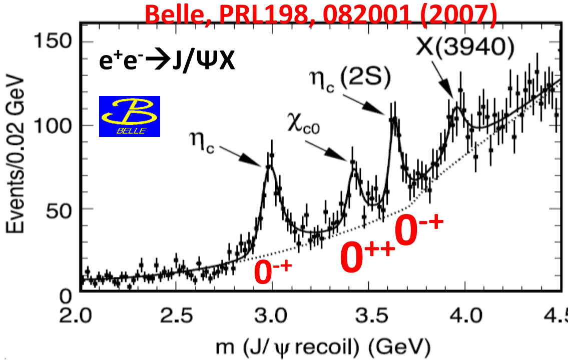
Belle,PRL 104, 112004 (2010)



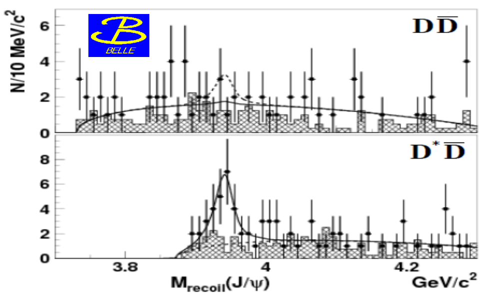
LHCb,PRD 95, 012002(2017)



Belle, PRL198, 082001 (2007)



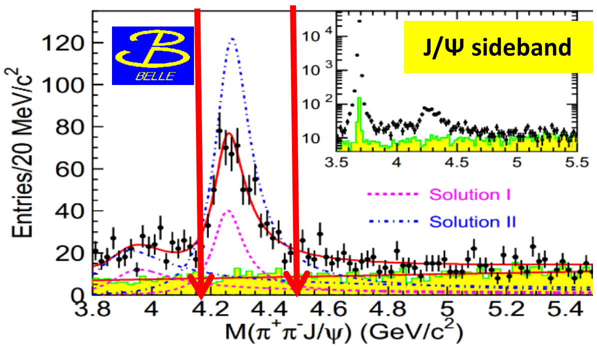
Belle, PRL100, 202001 (2008)

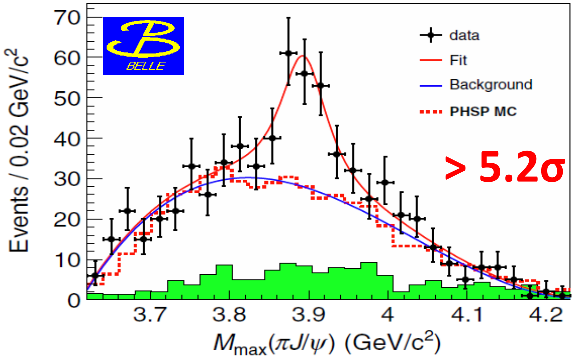


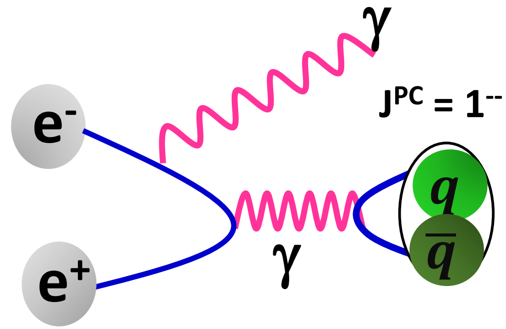
e⁺e⁻→J/ΨX(3940)

Double charmonium production, another interesting process through which Belle II can access C=+ even states.

Initial state radiation







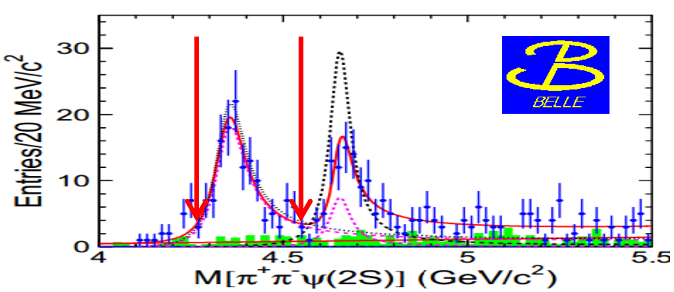
$$\frac{BR\left[Y(4260) \to Z(3895)^{\pm}\pi^{\mp}\right]}{BR\left[Y(4260) \to J/\psi\pi^{+}\pi^{-}\right]} = (29.0 \pm 8.9)\%$$

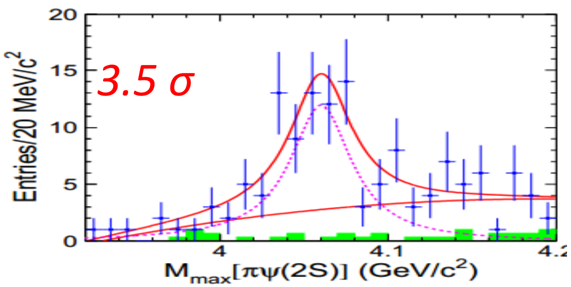
Measured properties

- Mass = (3894.5±6.6± 4.5) MeV
- Width = (63±24±26) MeV

- ➢ Belle II will compliment BESIII here.
- ➢ Expects improvement in mass resolution due to longer CDC
- ➢ One possible study $e^+e^- \to Y(\to J/\psi\pi^0\pi^0)\gamma_{ISR}$ for neutral partner

$e^+e^- \to \psi'\pi^+\pi^-$ study Belle, PRD 91, 112007 (2015)





Mass = (4054±3± 1) MeV
Width = (45±11±6) MeV

Any relation to $Z(4050)^+ \to \chi_{c1}\pi^+$?
Search $Z(4430)^+ \to \psi'\pi^+$ as in $B^0 \to \psi'\pi^+K^-$?

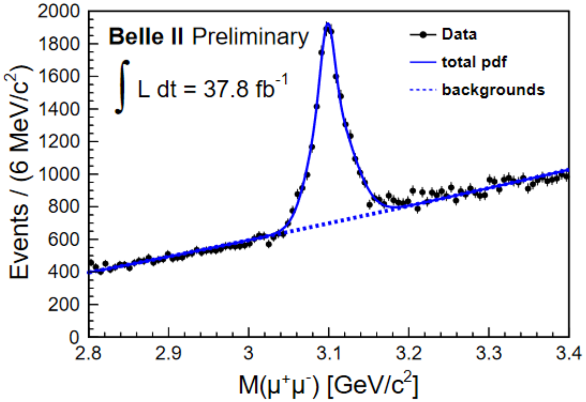
- ❖ One can also search for Z_{cs}^{+} in $e^+e^- \to J/\psi KK$.
- ❖ Further, interesting to study $e^+e^- \to D^0D^-\pi^+$ and $e^+e^- \to \Lambda_c^+\Lambda_c^-$.

ISR preliminary results

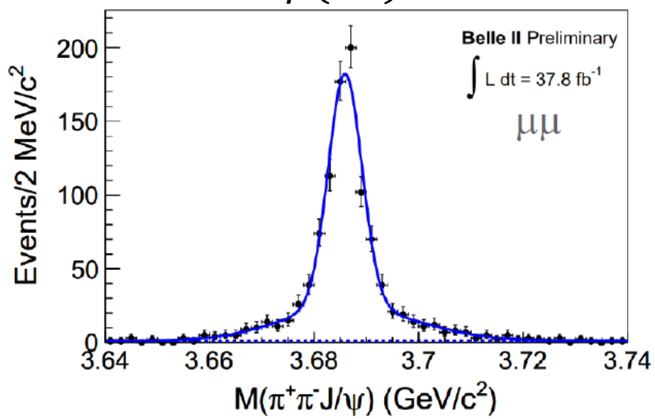
BELLE2-NOTE-PH-2020-060

$$e^+e^-\gamma_{ISR} \to \pi^+\pi^-J/\psi(\to \ell^+\ell^-)$$

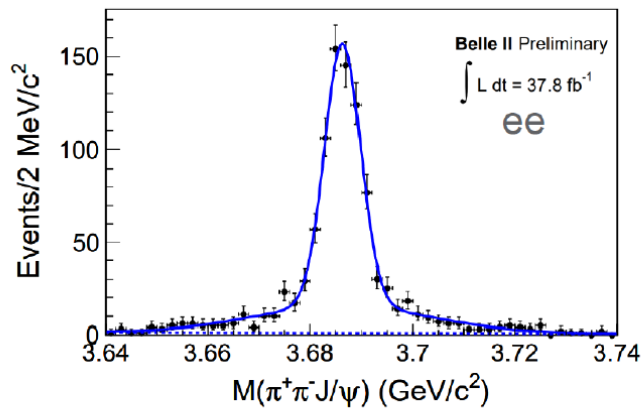
J/ψ



$\psi(2S)$

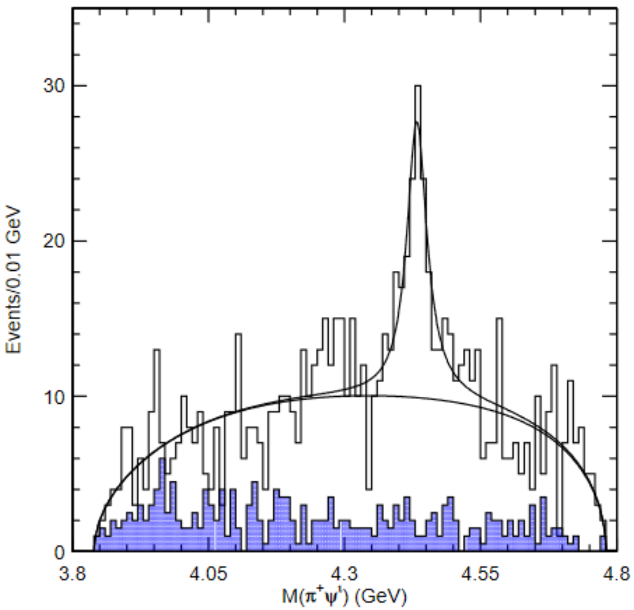


$\psi(2S)$



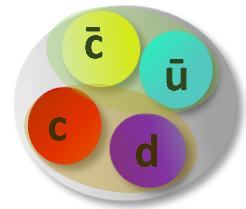
- Clear observation of ISR J/ψ and $\psi(2S)$ signal
- Soon, we can expect $Y(4260)$ rediscovery (~60 events per 100 fb^{-1})

Z : "with a charge"



Belle observed a peak like structure, $Z_c^+(4430)$, in $B \to [\psi(2S)\pi^+]K^-$ in 2008 with 6.5σ.
They observed the charged state

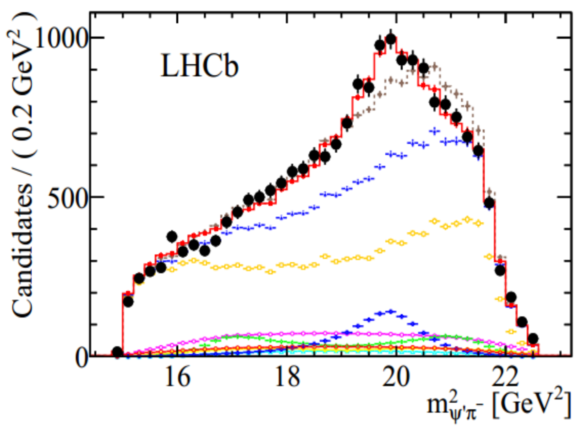
$$M = (4433 \pm 4 \pm 2)\ \text{MeV}$$
$$\Gamma = (45^{+18+30}_{-13-13})\ \text{MeV}$$



For long time, there was a conflict. Belle re-performed the analysis with more data (with amplitude analysis) and came with similar conclusion

- It was only after BESIII, Belle discovery of $Z_c^+(3900)$ in 2014 tetra-quark was taken seriously.
- Further, same year LHCb confirmed the discovery of $Z_c^+(4430)$.
- That lead to a new revolutionary change.

LHCb, PRL112, 222002 (2014)

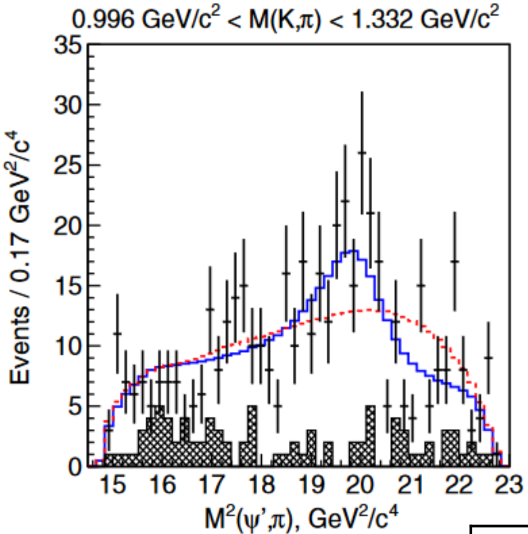


4D fit ($M_{\Psi(2S)\pi+}$, $M_{K\pi}$, $\cos\Theta_{\Psi(2S)}$ and ϕ) by LHCb confirm the Existence of $Z^+(4430)$

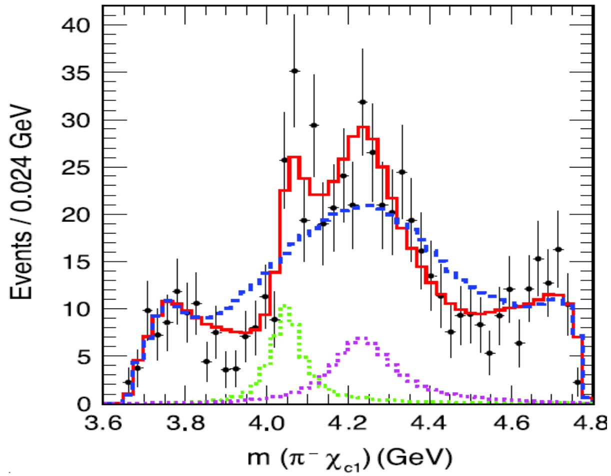
$$M = (4475 \pm 7^{+15}_{-25})\ \text{MeV}$$
$$\Gamma = (109 \pm 13^{+37}_{-34})\ \text{MeV}$$

Z : “with a charge”

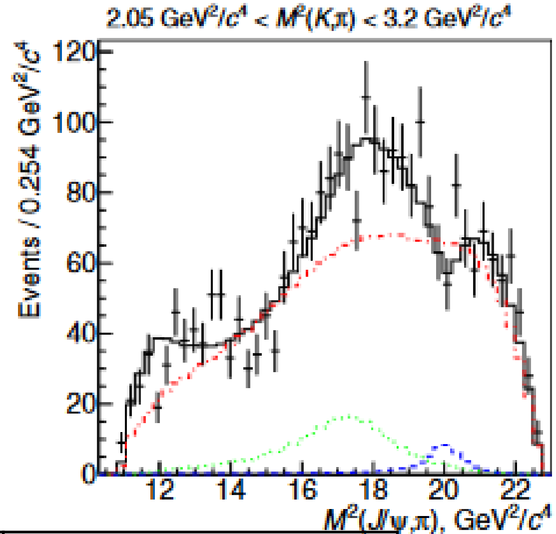
Belle,PRD 88, 074026 (2013)



Belle, PRD80, 031104 (2009)



Belle, PRD80, 031104 (2009)



	Name	M (MeV/c²)	Γ (MeV)	J^P	Process
$(D^*D^*)^+$	$X(4050)^+$	$4051\,^{+24}_{-43}$	$82\,^{+51}_{-55}$	$?^?$	$B\to(\chi_{c1}\pi^+)K^-$
	$X(4200)^+$	$4196\,^{+35}_{-37}$	$370\,^{+99}_{-149}$	1^+	$B\to(J/\psi\pi^+)K^-$
$(D_0D_1)^+$	$X(4250)^+$	$4248\,^{+185}_{-45}$	$177\,^{+321}_{-72}$	$?^?$	$B\to(\chi_{c1}\pi^+)K^-$
$(D_1D^*)^+$	$X(4430)^+$	4477 ± 20	181 ± 31	1^+	$B\to(\psi'\pi^+)K^-$ $B\to(J/\psi\pi^+)K^-$

- Perform Dalitz analyses with more statistics: help in measuring and understanding these states with precision.
- At Belle II, search for new states using $B^0\to(\chi_{c2}\pi^-)K^+$ decay mode.
  - At 10 ab⁻¹, yield comparable to current Belle yield of $B^0\to(\chi_{c1}\pi^-)K^+$
- Possible study of $B^0\to(c\bar{c})\pi^0K^+$ in search for neutral partners.

Bottomonium at Belle

Unique at B-factories

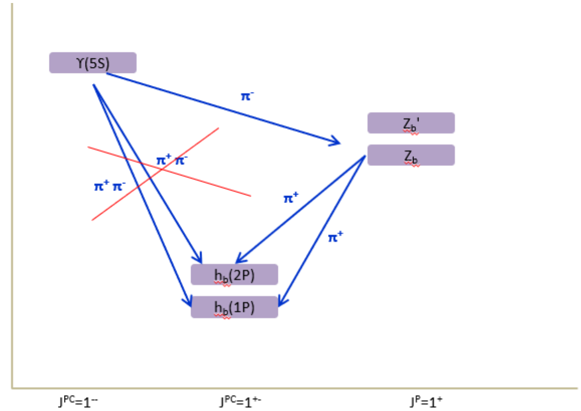
Bottomonium spectrum is significantly different from charmonium spectrum.

Z_b states were found in the $\Upsilon(5S)$ decays and were clear signature of *exotic* state.

Production ratio

Belle, PRL 108 032001 (2012)

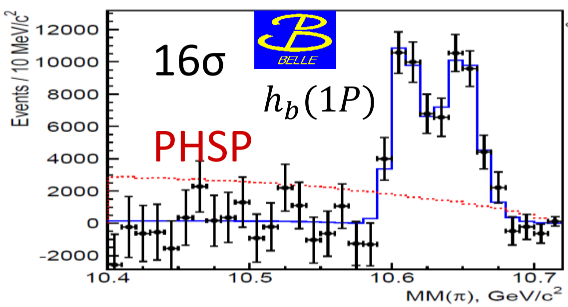
$$\frac{\Gamma(\Upsilon(5S)\to h_b(nP)\pi^+\pi^-)}{\Gamma(\Upsilon(5S)\to \Upsilon(2S)\pi^+\pi^-)} = \begin{cases} 0.45 \pm 0.08^{+0.07}_{-0.12} & \text{for } h_b(1P) \\ 0.77 \pm 0.08^{+0.22}_{-0.17} & \text{for } h_b(2P) \end{cases}$$

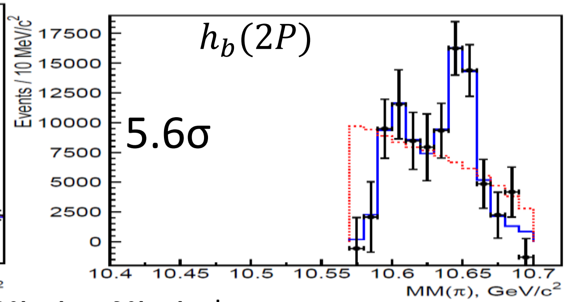


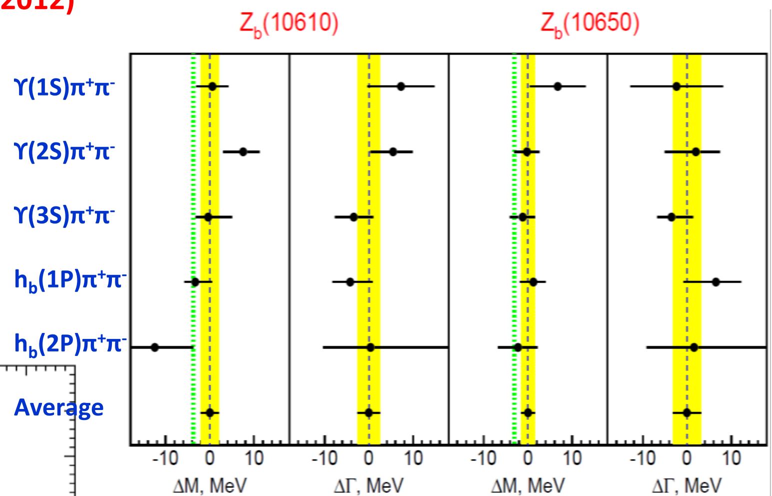
Decay to h_b should be suppressed due to spin flip !

$\Upsilon(5S) \rightarrow h_b(nP)\pi^+\pi^-$ decay mechanism seems to be *eXotiC*

Fit MM(π) in M(h_bπ) bins **Belle, PRL 108, 122001 (2012)**

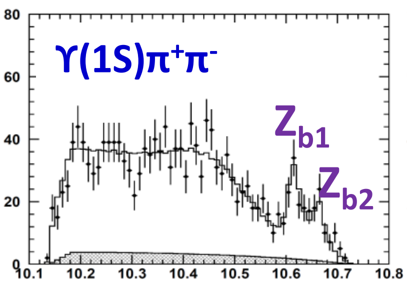




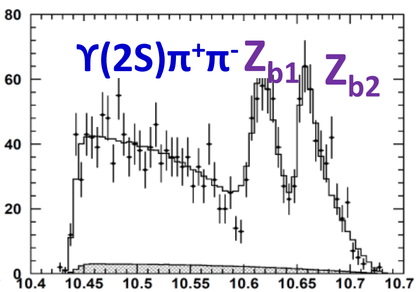


B*B threshold B*B* threshold

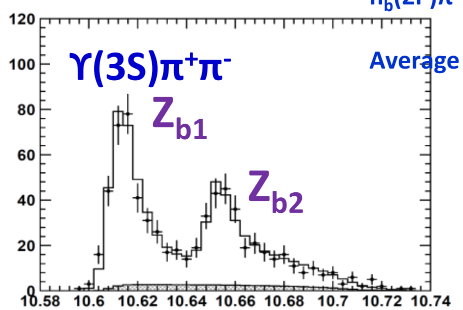
Resonant structure of $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$



M(Υ(1S)π)$_{max}$



M(Υ(2S)π)$_{max}$



M(Υ(3S)π)$_{max}$

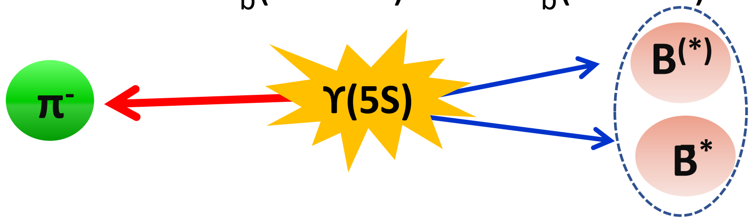
More precise measurements.

More on Z_b

$B^+ \to J/\Psi K^+$, $B^+ \to D^0(\to K^+\pi^-)\pi^+$, $B^+ \to D^0(\to K^+\pi^-\pi^+\pi^-)\pi^+$, $B^0 \to J/\Psi K^{*0}(\to K^+\pi^-)$, $B^+ \to D^-(\to K^+\pi^+\pi^-)\pi^+$, $B^0 \to D^{*-}(\to \bar{D}^0[\to K^+\pi^-]\pi^-)\pi^+$, $B^0 \to D^{*-}(\to \bar{D}^0[\to K^+\pi^-\pi^+\pi^-]\pi^-)\pi^+$ and $B^0 \to D^{*-}(\bar{D}^0[\to K^+\pi^-\pi^0]\pi^-)\pi^+$

$\Upsilon(5S) \to B^*B^{(*)}\pi$

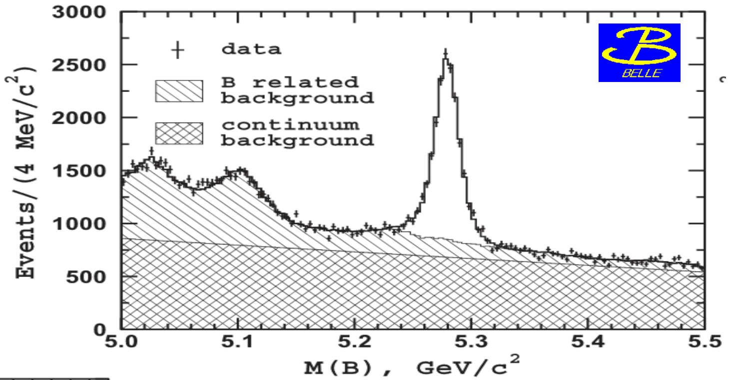
Masses of $Z_b(10610)^+$ and $Z_b(10650)^+$ close to BB^* and B^*B^* threshold



One B is fully reconstructed

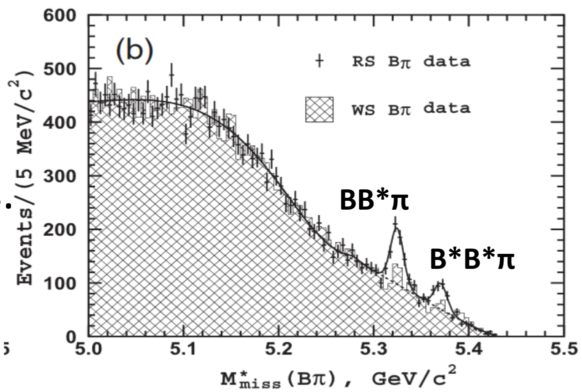
B is combined with π and recoil mass to (Bπ) combination is calculated

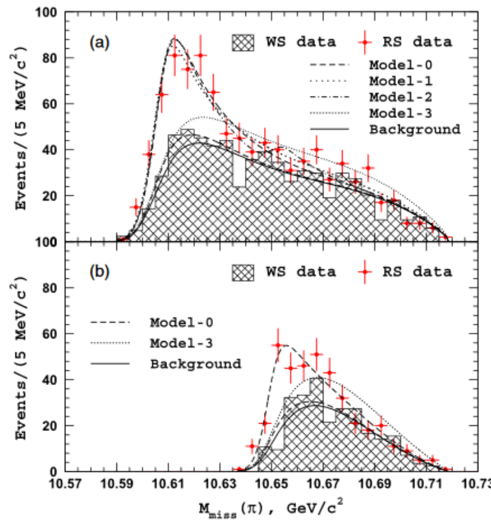
$$rM(B\pi) = \sqrt{E_{cms}^2 - P_{B\pi}^2}$$



Belle, PRL116, 212001 (2016)

- $Z_b(10610)^+$ in BB^* and $Z_b(10650)^+$ seen in BB^*/B^*B^*.
- $B^{(*)}B^*$ dominant mode of Z_b decays.

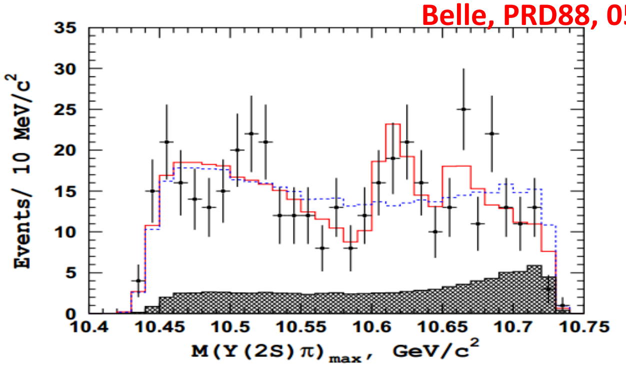


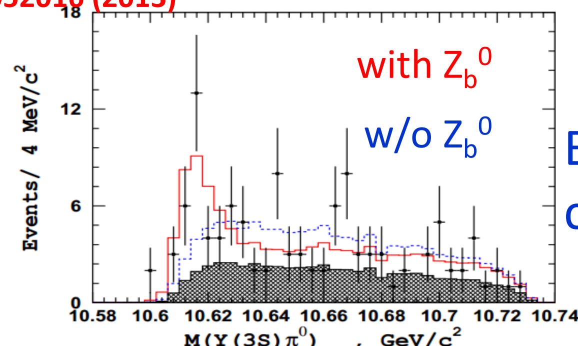


Belle II can confirm Z_b relation to $B^{(*)}B^*$.

Neutral Z_b^0 in $\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$

Belle, PRD88, 052016 (2013)





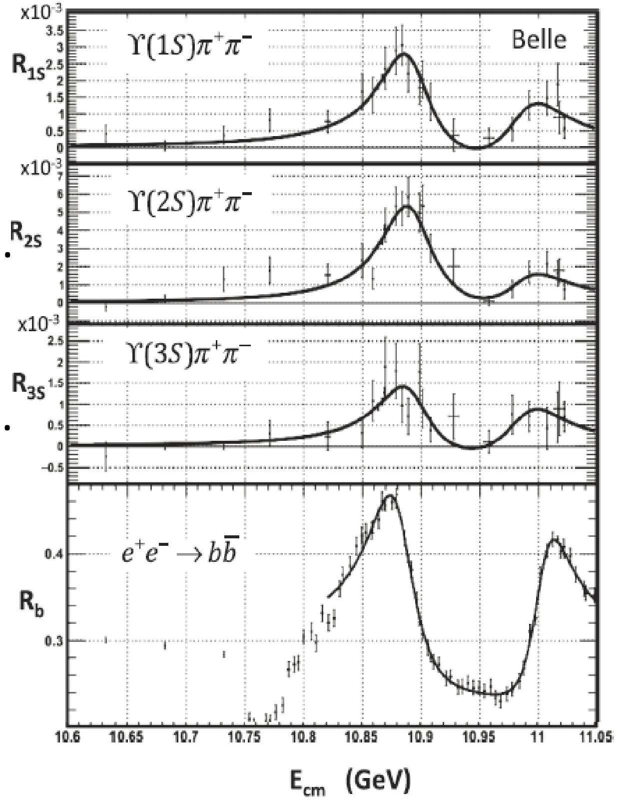
Belle II can study neutral Z_b^0 and confirm in other modes also.

Energy scan

Belle, PRD 91, 072003 (2015)

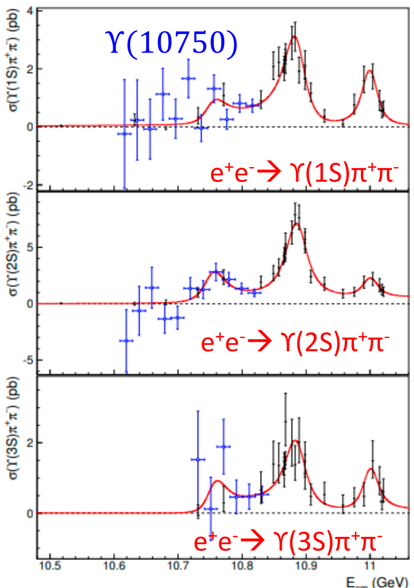
- Many quarkonium-like states were found in energy scans in *ISR*, Y(4008) and Y(4260) in $J/\psi\pi^+\pi^-$, Y(4360) and Y(4660) in $\psi'\pi^+\pi^-$, ψ(4050) and ψ(4160) in $J/\psi\eta$.
  - ➢ Peaks observed in the cross-section depend on final state.

- Recent energy scan of $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$ (n=1,2,3) cross sections by Belle, show situation is different in bottomonium-like states.
  - ➢ All of cross-sections exhibits peaks at **ϒ(10860)** and **ϒ(11020)** resonances that are also seen in total hadronic cross sections.



Energy scan of $e^+e^- \rightarrow h_b(nP)\pi^+\pi^-$ (n=1,2)

Belle, PRL 117, 142001 (2016)



High stat scan point

- ❖ Belle observe a new structure in the energy dependence.
- ❖ The global significance is 5.2σ
- ❖ $M = (10752.7 \pm 5.9^{+0.7}_{-1.1})$ MeV/c^2
- ❖ $\Gamma = (35.5^{+17.6+3.9}_{-11.3-3.3})$ MeV
- ❖ New structure could have a resonant origin and correspond to a signal for not yet observed $\Upsilon(3D)$ state provided S-D mixing is enhanced or an exotic state.

Belle, JHEP 10 (2019) 220

Current statistics is limited and Belle II will play crucial role here.

Transition from Υ(5,6S) to molecular states

With unique data set at Υ(6S), Belle II can understand the $\Upsilon(6S) \rightarrow Z_b$ decay

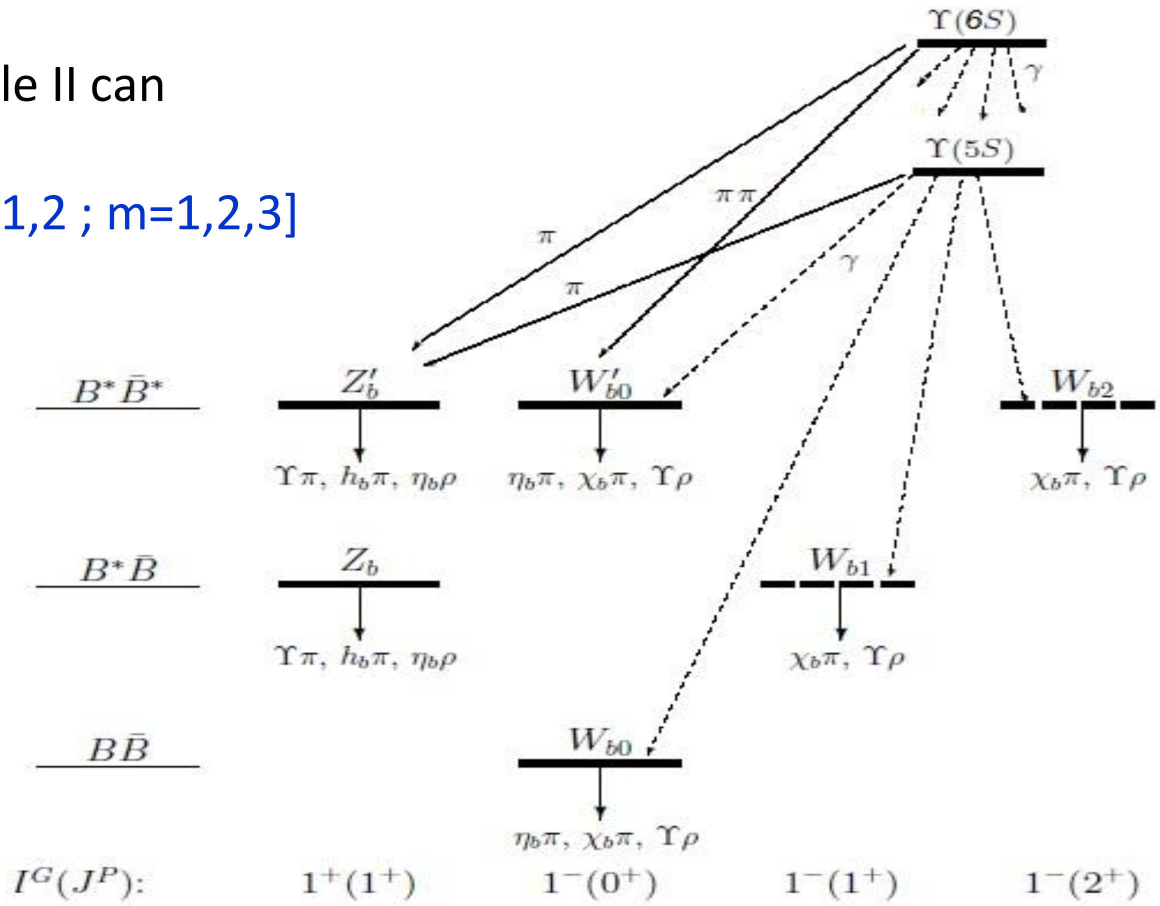
$\Upsilon(6S) \rightarrow h_b(nP)\ \pi^+\pi^-$, $\Upsilon(mS)\ \pi^+\pi^-$ [n=1,2 ; m=1,2,3]

If Z_b molecular state, then Heavy Quark Spin symmetry suggest there should be 2/4 molecular partner bottomonium-like state (W_b)

$\Upsilon(5S,6S) \rightarrow W_{b0}\ \gamma$

$\Upsilon(6S) \rightarrow W_{b0}\pi^+\pi^-$

$W_{b0} \rightarrow \eta_b\pi, \chi_b\pi, \Upsilon\rho$

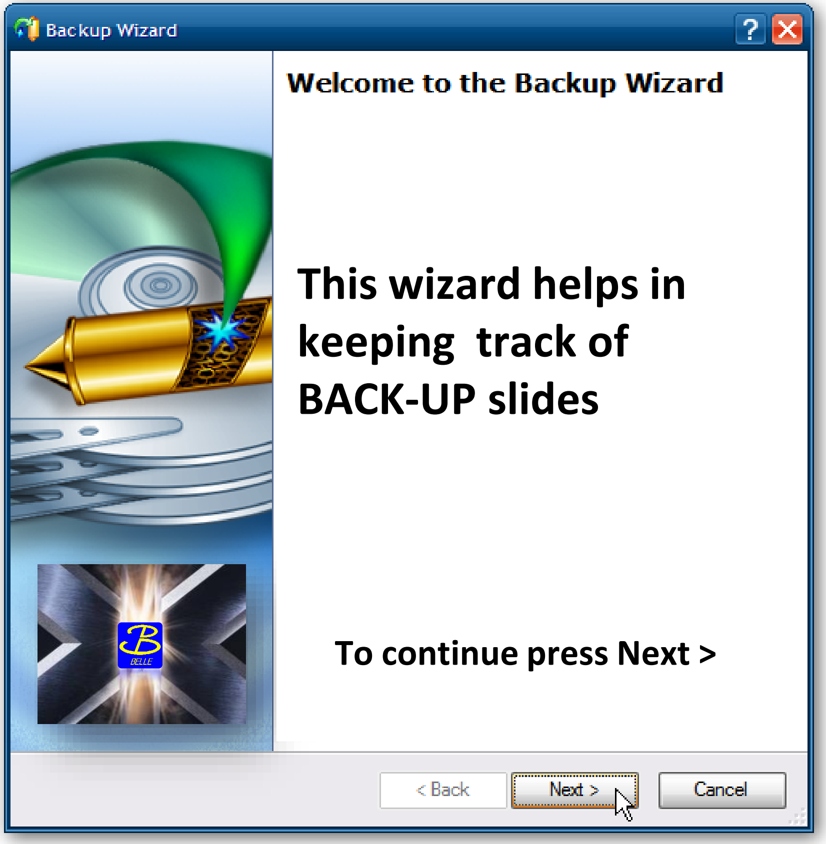


Voloshin, PRD 84, 031502(R)(2011)

Future summary

- Quarkonium sector is not as simple as one expects.
- Many new states have been found with puzzling nature.
- Still not fully understood in spite of the best efforts by all the experiments.
- Belle II will play an important role along with LHCb and BESIII to understand them.
- Belle II detector already started collecting data and hope to provide fruitful results soon.

Thank you


Backup Wizard
Welcome to the Backup Wizard
This wizard helps in keeping track of BACK-UP slides
To continue press Next >
< Back
Next >
Cancel

Search for $R^{++} \to \mathrm{D}^+\mathrm{D}_s^{*+}$

Belle, PRD 102, 112001 (2020)

By exchanging a kaon, a $D^+D_{s0}^{*+}(2317)$ molecular state can be formed (regardless of whether $D_{s0}^{*+}(2317)$ is a $c\bar{s}$ state or a DK molecule).

M.S. Sanchez et al, PRD 98, 054001 (2018)

One expect to have the molecule state at 4140 MeV/c^2 as (denote as R^{++})

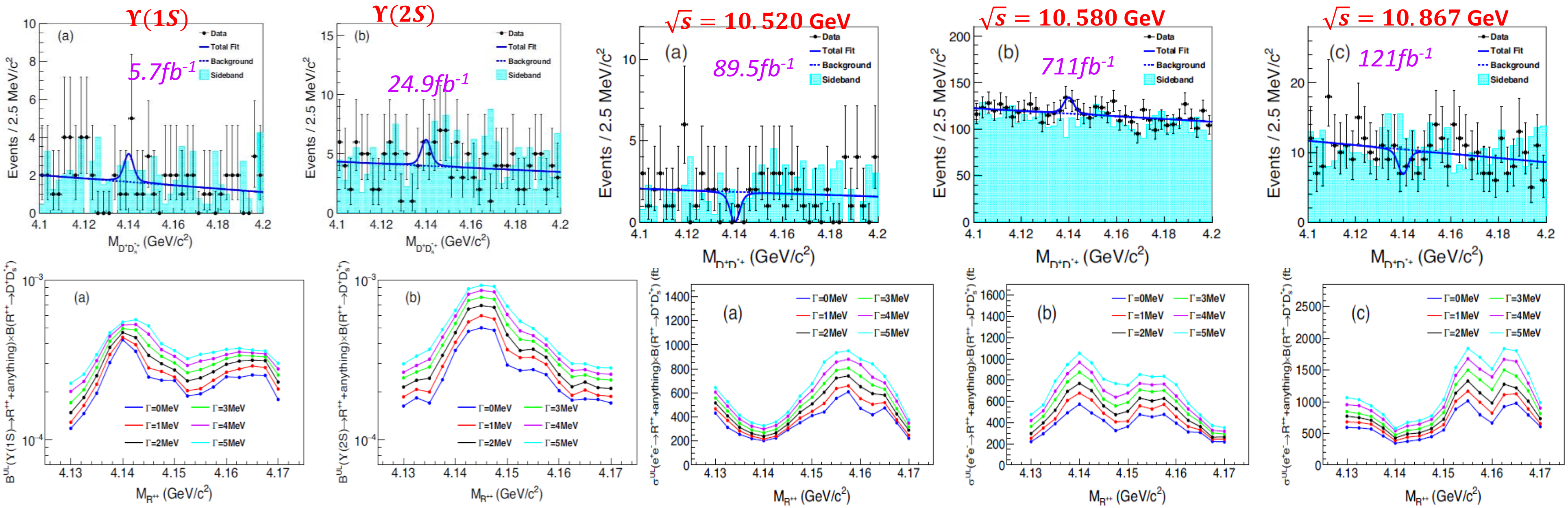
A.M. Torres et al, PRD 99, 076017 (2019)

A doubly-charged and doubly-charmed molecule R^{++} expected to decay to $\mathrm{D}^+\mathrm{D}_s^{*+}$ with modest rates.

Mass of R^{++} is predicted to be in the range of 4.13-4.17 GeV/c2 with width of (2.3-2.5) MeV.

$e^+e^- \to D^+D_s^{*+} + X$ $\quad D^+ \to \mathrm{K}^-\pi^+\pi^+$ and $D^+ \to K_S^0(\to \pi^+\pi^-)$ $\quad \mathrm{D}_s^+ \to \phi\pi^+$ and $D_s^+ \to K^*(892)^0\, K^+$

R^{++} mass of 4.14 GeV/c^2 with a width of 2 MeV.



More precise search can be carried out at Belle II !